Light-Actuated Micromechanical Relays for Zero-Power Infrared Detection

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Abstract: *This paper reports on the demonstration of passive light-actuated micromechanical relays (LMRs) for near-zero power infrared (IR) detection. Differently from any existing switching element, the proposed LMR relies on a plasmonically-enhanced thermomechanical coupling to selectively harvest the impinging IR energy, in a specific spectral band of interest, and use it to mechanically create a conducting channel between the device terminals without the need of any additional power source, which directly translates into a near-zero standby power consumption. The prototypes presented here are selectively activated by a narrow band radiation in the mid-wavelength IR spectral region (~5.5 μm). The strong and spectrally selective absorptivity and the high thermomechanical coupling of the fabricated structure result in the first experimental demonstration of LMRs with high reliability (>1000 cycles) and ultra-low actuation thresholds (~ 1 μW) suitable for the realization of a new class of zero-power IR digitizers capable of producing a quantized output bit in the presence of a unique IR spectral signature of interest.*

Keywords: zero-power sensor; infrared detector; micromechanical relay; switch; plasmonic absorber.

Introduction

Due to the fast development of the Internet of Things, there is a growing need for unattended ground sensors that can remain dormant, with near-zero power consumption, until awakened by an external trigger or stimulus. Light-activated switches utilizing photodiodes, light-sensitive resistors or phototransistors [1] have been widely used for light sensing and light-controlled automation. However, they consume power continuously, regardless of the presence of the triggering radiation, which severely limits the sensors' lifetime. This work fundamentally breaks the paradigm of using active power to implement light-controlled ON/OFF switching while simultaneously achieving a large and abrupt change in conductivity (*~10* orders of magnitude), for sub-μW threshold values. Furthermore, differently from any existing light-controlled switch, the triggering spectral band of the proposed LMR can be defined lithographically on chip enabling the monolithic fabrication of multiple LMRs connected together to form a logic topology suitable for the detection of specific spectral signatures.

Device Design

The LMR consists of two symmetric released cantilevers facing each other as shown in Figure 1. Each cantilever is composed of a head, an inner pair of thermally sensitive bimaterial beams for actuation and an outer pair of identical bimaterial beams for temperature and stress compensation. The inner and outer beams are connected by a thermal isolation link. A lithographically defined plasmonic absorber (Fig. 2, 3) [2-4] is integrated in the head of one cantilever while the head of the other cantilever is covered by a relatively thick gold layer as an IR reflector. The absorbing head carries a high stiffness bowl-shaped platinum tip electrically connected to one of the device terminals while the second terminal contact is defined on the opposite head and separated by a sub-μm air gap (Fig. 2). When IR radiation, matching the defined absorption band, impinges on the device from the top, it is exclusively absorbed by the plasmonic head, leading to a temperature increase of the corresponding cantilever up to the thermal isolation links [5]. Such IR induced temperature rise results in a downward bending of the corresponding thermally sensitive pair of bimaterial beams (Fig. 1b) and, therefore, in a vertical displacement of the metal tip which is brought into contact with the opposite terminal when the absorbed IR power exceeds the designed threshold.

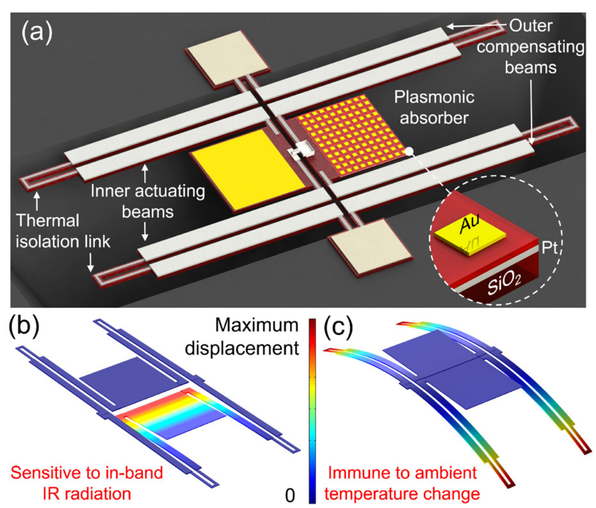

Figure 1. (a) Three dimensional (3D) mock-up of the LMR. (b) 3D finite element method (FEM) simulated deflection of the LMR in response to in-band IR radiation, selectively absorbed by the plasmonic head, and (c) under ambient temperature changes.

Aluminum (Al) and silicon dioxide (SiO_2) were chosen for the bimaterial beams due large difference in the values of their thermal expansion coefficients ($\alpha_{Al}=23.1\times10^{-6}\ K^{-1}$, $\alpha_{SiO2}=0.56\times10^{-6}\ K^{-1}$) which results in a large bending (i.e. tip displacement) for a given temperature variation. Despite the intrinsically high sensitivity of the LMR to the absorbed radiation, the structure is completely immune to ambient temperature changes and residual stress thanks to the built-in compensation mechanism illustrated in Figure 1c. The threshold power of the LMR is primarily determined by the dimensions of the cantilevers and the size of the air gap given a fixed material stack of the bimaterial beams. LMRs with different thresholds ranging between *1 μW* and *3 μW* were designed and fabricated (Fig. 2).

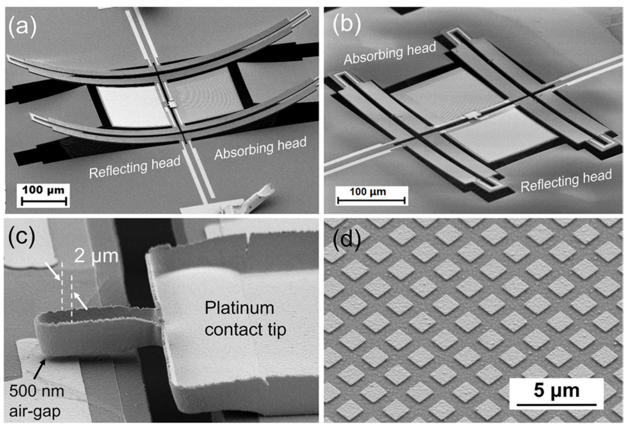

Figure 2. SEM images of (a) a 1-μW threshold LMR and (b) a 3-μW threshold LMR. (c) and (d) show close-up views of the platinum contact tip and nano structures of the plasmonic absorber, respectively.

Experimental Results

The absorption spectrum of the plasmonic absorber was measured by Fourier transform infrared (FTIR) spectrometer (Fig. 3) showing a near-unity absorption *~95%* at *5.5 μm* with a full width at half maximum (FWHM) of *~1.1 μm*.

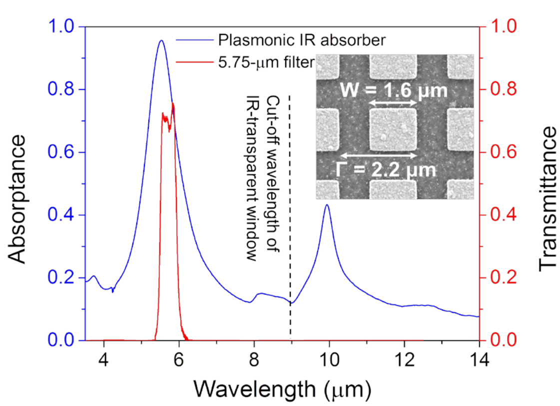

Figure 3. Absorption spectrum of the fabricated plasmonic IR absorber and transmission spectrum of the bandpass IR filter used in the blackbody test. The inset shows the top-view SEM image of the absorber with 1.6-μm gold patches.

The fabricated devices were tested in a vacuum chamber equipped with an IR-transparent window and a calibrated blackbody source mounted on top it. The IR beam spot was large enough to cover the entire chip (1×1 cm^2) under test. A 5.75-μm bandpass IR filter (Fig. 3) was mounted in front of the beam outlet in the test of the 1-μW device. First the temperature of the blackbody was set to *515 °C*. An absorbed power *~1.05 μW* was extracted based on the calibrated power density, the area of the absorbing head and the absorptance of the plasmonic absorber (Fig. 3). As expected, the LMR turned ON and showed reversible ON/OFF state transitions when exposed to the chopped 5.75-μm IR radiation (Fig. 4a). Then the 3-μW threshold device was tested with 1000°C blackbody radiation without a filter. The absorbed power was estimated to be *~10 μW* and found be sufficient to switch ON the device. The blackbody radiation was then mechanically chopped at *1 Hz* demonstrating reliable switching of the LMR for more than *1000 cycles* without failure (Fig. 4b). When the blackbody radiation was off, the presence of an air gap separating the device terminals enables the achievement of extremely low leakage ($<10^{-12}\ A$ measured, limited by the noise from the sourcemeter and cables), which drastically reduces the standby power consumption to near-zero values. These experimental results demonstrate a proof of concept of the proposed LMR for the realization of zero-power infrared detection.

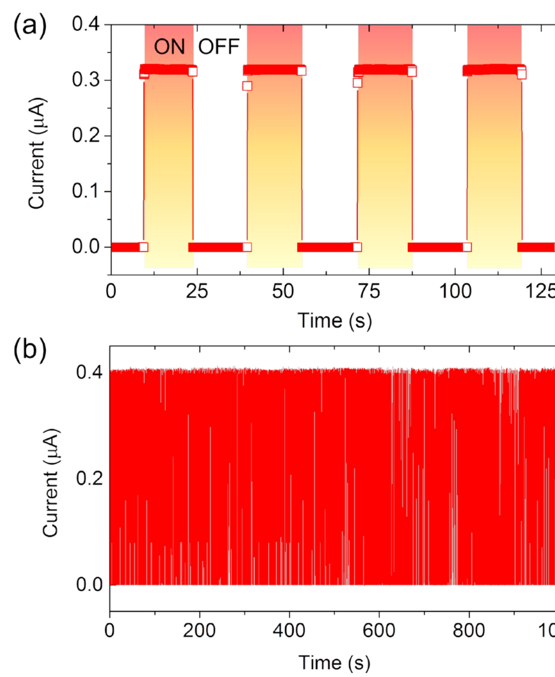

Figure 4. Measured current (for a 1 mV applied bias) through the (a) 1-μW threshold LMR and (b) 3-μW threshold LMR in response to mechanically chopped blackbody radiation. The 3-μW device was operated over 1000 cycles without failure. Such a large and abrupt change in conductivity, in response to ~μW electromagnetic power, is not achievable with any of the existing light-controlled switching technologies.

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